INNOVATIVE TECHNOLOGY
Summary Report

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Passive Reactive Barrier

Subsurface Contaminants
Focus Area

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INNOVATIVE TECHNOLOGY
Summary Report

Passive Reactive Barrier

Tech ID 46

Subsurface Contaminants
Focus Area

Demonstrated at
Oak Ridge National Laboratory
Oak Ridge Reservation
Oak Ridge, Tennessee

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://www.em.doe.gov/ost under "Publications."

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SECTION 1
SUMMARY

Technology Summary

Problem

Numerous governmental, commercial, and industrial sites associated with weapons production, nuclear power generation, equipment maintenance, chemical production, mining, oil refineries, and semiconductor manufacturing have groundwater contaminated to such a degree that the concentrations of organic and inorganic constituents must be reduced to acceptable levels using some method of *in situ* or *ex situ* treatment. U.S. Department of Energy (DOE) sites alone have over 1.7 trillion gallons of groundwater that require some degree of remediation. While many technologies are available to address different groundwater contaminants, not all technologies are suitable to meet site-specific and contaminant-specific requirements.

The baseline groundwater remediation technology is the pump and treat system, which uses one or more extraction wells to collect the contaminated groundwater and pump it to a surface treatment plant. These systems typically require multiple wells to extract the contaminated water from the aquifer and, in many instances, the constituents of concern (COCs) are not adequately captured or treated. This active treatment approach can be equipment and energy intensive, depending upon the complexity of the extraction system and the degree of treatment required to control and mitigate the contaminant plume. Additionally, this conventional system may not be effective in removing or reducing contaminant concentrations to acceptable levels within the aquifer. Increased costs will be incurred to obtain the required environmental permits, to perform more extensive treatment (if required), or to construct additional injection wells. In some instances, additional constituents, other than the identified COCs, will have to be treated before final disposal of the water.

How It Works

Passive Reactive Barrier (PRB) technology can be used to reduce contaminant concentrations in groundwater, under a wide variety of site-specific and contaminant-specific conditions. The PRB technology employs a conventional impermeable barrier installed vertically in a sand- or aggregate-filled trench to intercept and direct contaminated groundwater to a treatment unit (reactive material) that can be selected to target specific contaminant(s) for removal or stabilization (MSE 1998a). As illustrated in Figure 1, the PRB takes advantage of the local groundwater flow regime and hydraulic gradient to capture the contaminant plume and direct it towards and through the treatment zone.

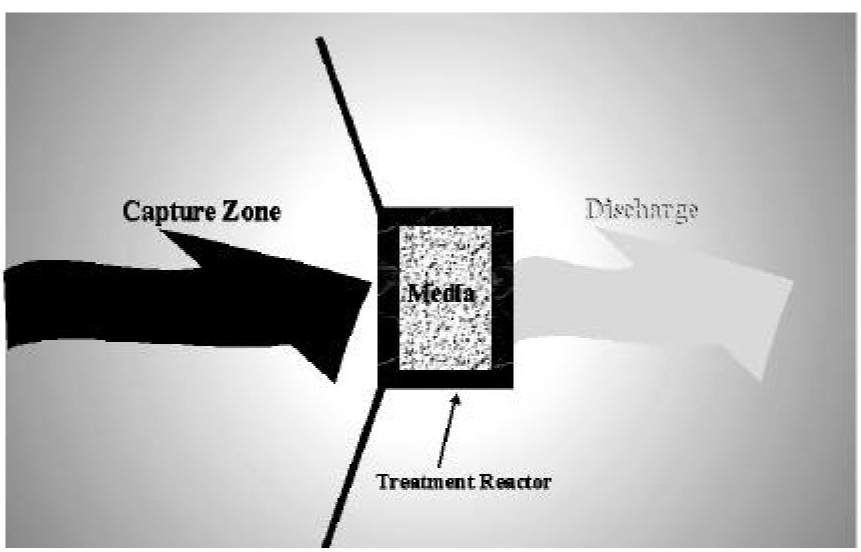

Figure 1. Typical funnel and gate passive reactive barrier schematic.

The PRB technology is routinely installed in, or connected to, a sand-filled trench and is referred to differently depending upon the orientation of the treatment zone to the trench:

- As depicted in Figure 1, the Funnel and Gate PRB (FGPRB) employs angled wing walls to capture and direct the contaminated groundwater to a central treatment unit. The sand-filled trench is comprised of a collection side and a discharge side, with the impermeable barrier separating the two.
- The Trench PRB (TPRB) utilizes a groundwater capture trench that is installed subparallel to the direction of groundwater flow, with the impermeable barrier located on the down gradient side of the trench. Contaminated groundwater is collected through the capture zone portion of the trench and then directed through the treatment zone in the trench, prior to discharge from the end of the trench.

It is essential that the hydrogeology of the site be well understood, so that construction of the PRB can take advantage of the hydraulic properties of the site. A strong horizontal groundwater flow direction and gradient at the site, coupled with a relatively impermeable lower boundary and minimal deeper groundwater inflow, will help operation of the system greatly.

This is a passive treatment system with very low energy requirements. The local hydrogeological flow system provides the energy to capture and direct the contaminated groundwater to the treatment unit, while a minor amount of external energy is required to operate the treatment unit pumps and the internal monitoring system. The reactive material in the treatment zone can be designed to target specific compounds identified in the contaminant plume.

Potential Markets

The PRB technology has the potential to address groundwater contamination in a variety of settings, provided that the contamination area is limited, the contaminant and site characteristics are well defined, and the depth of contamination is relatively shallow (less than 50 feet). The usefulness of the PRB technology is directly dependent upon the ability to: (1) select a reactive material that will remove or stabilize the identified contaminants; (2) collect the contaminated groundwater; and, (3) direct this water through the treatment zone. DOE, U.S. Department of Defense (DoD), other federal and state governments, and private sector organizations have numerous sites across the country where contaminant concentrations must be reduced. Depending upon site-specific hydrogeologic and contaminant characteristics, the PRB technology may be a viable approach to mitigate the contaminants at these sites. Both organic and inorganic contaminants are amenable to treatment by this technology.

Advantage over the Baseline

The advantages of the PRB technology over the baseline technology include:

- it is a passive treatment system with very low energy requirements;
- the hydrogeological flow system provides the energy to capture and direct the contaminated groundwater to the treatment unit and external energy is only required to operate the treatment unit pumps and the internal monitoring system;
- the drastically reduced operating costs offset the higher construction costs that are typical for the PRB, which results in an overall reduction in the life-cycle cost for this technology;
- the PRB leverages the site hydrogeological characteristics to capture the contaminant plume, which enables it to work in relatively low-permeability materials that are not suitable for pump and treat systems; and,
- specific COCs are rapidly removed, or stabilized, from the groundwater as they pass through the treatment unit (reactive material), thereby reducing the required treatment time. While the same reactive material should be just as effective in removing the COCs when used in a pump and treat system, problems with extraction-well capture zones (especially in low-permeability settings), development of preferential groundwater flow pathways, and other inefficiencies combine to make the PRB technology more effective under certain situations.

Potential disadvantages of the PRB technology are that:

- it is limited to relatively shallow depths (less than 50 feet) because of construction challenges associated with installation of the impermeable barrier;
- to be effective, the impermeable barrier must be constructed to intercept a large portion of the contaminated area and configured to direct the captured groundwater to the treatment unit (gate);
- inflow of groundwater from deeper flow systems must be prevented or controlled to minimize adverse impacts to the operation of the PRB technology;
- the hydraulic properties and treatment characteristics of the PRB must be consistent with the requirements of a gravity-driven flow regime;
- operating costs associated with periodic replacement of the reactive material, may be incurred; and
- in a setting with a very low hydraulic gradient, barrier construction modifications, installation of pumps, or operational changes may be required to overcome the frictional losses in the treatment unit so that the captured groundwater will move through the treatment unit and contaminant removal will occur.

Demonstration Summary

Demonstration Site

This report covers the period of 8/97 – 8/99 and summarizes the results of two PRB technology demonstrations, which were installed to intercept the S-3 Ponds Uranium Plume at the Oak Ridge Reservation (ORR) Y-12 Plant, Oak Ridge, Tennessee. These demonstrations addressed the shallow groundwater contaminant plumes designated as Pathway 1 and Pathway 2 (see Figure 2), which had uranium concentrations of up to 2.6 milligrams per liter (mg/L) and 1.7 mg/L, respectively. The plumes originated from a group of four unlined ponds, designated as the S-3 Ponds (see Figure 3), and discharged into Bear Creek. The ponds received large volumes of liquid wastes that discharged to the shallow grou m of the pond

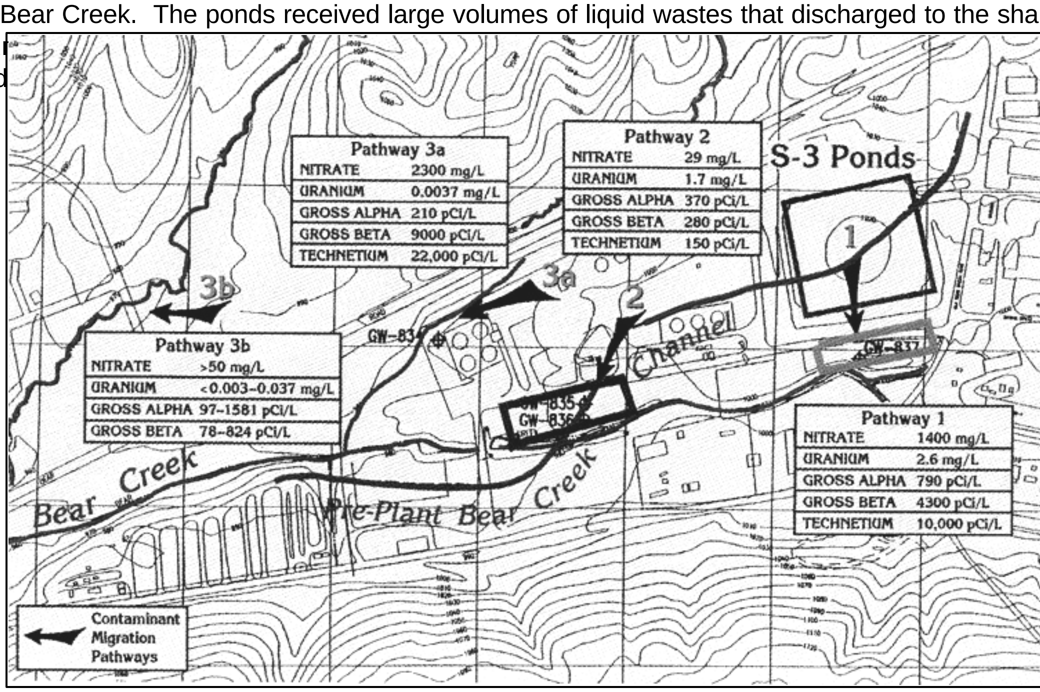

Figure 2. S-3 ponds site map.

Targeted Problem

The specific problem at the S-3 Ponds site was the ongoing discharge of uranium into Bear Creek. Groundwater flow is generally from northeast to southwest, originating in the area of the former S-3 Ponds, flowing underneath the Y-12 Plant parking lot, and discharging into the bed of Bear Creek. Previous attempts at trying to control the contaminant plume with conventional pump and treat technology were unsuccessful, due to the relatively low permeability of the shallow groundwater flow regime.

Figure 3. The S-3 ponds.

Site Characteristics

As determined through previous investigations, the site is underlain by the Ordovician age Nolichucky Formation, which consists of shale, interbedded with intraclastic limestone, thick fossiliferous limestone, and oolitic limestone. The bedrock unit has a strike of N55^{o}E and a dip of 45^{o}SE, which is parallel to the trend of the Bear Creek Valley (Watson, 1999). The soil at the site is 20 to 30 feet thick and consists of a silty to clayey residuum (weathered from the Nolichucky formation), man-made fill, alluvium, and colluvium. The overall permeability of this unconsolidated soil is relatively low; however, a transition zone of weathered and fractured bedrock (saprolite) is present between the soil and the competent bedrock. This transition zone, including remnant bedding in the saprolite, provides a higher permeability zone.

Waste disposal activities at the S-3 Ponds site resulted in three migration pathways: Pathway 1 and Pathway 2 that are confined to the shallow unconsolidated zone and Pathway 3, which is a deep migration pathway in the bedrock. Overall, the contaminant plume extends approximately 4,000 feet along strike and to a depth of about 400 feet (in Pathway 3). Pathway 1 was addressed with a FGPRB, while a TPRB was demonstrated at Pathway 2. The Pathway 3 contaminant plume was not included in the ORR PRB demonstration project. Both Pathway 1 and Pathway 2 contaminant plumes are confined to the shallow residuum, with discharge into the bed of Bear Creek. The primary COC for both Pathway 1 and Pathway 2 is uranium, with technetium, nitrate, and sulfate identified as secondary COCs. The PRB was a good candidate technology for the Pathway 1 and Pathway 2 contaminant plumes because the site geology was relatively well known and the depth of contamination in these plumes was relatively shallow.

Key Results

A FGPRB was installed to treat the Pathway 1 contaminant plume; approximately 133,000 gallons of contaminated groundwater were treated, with a reduction in the uranium concentration from 80.0 to 99.6 percent over the demonstration period. The reduction in the concentrations of secondary COCs (technetium-99 [51.6%], nitrate [75%], and sulfate [42%]) was not as great. The system did not operate in an entirely passive mode. To accommodate a relatively flat hydraulic gradient, electrical pumps were installed to ensure that adequate flow was maintained through the system and to counteract a build up in hydraulic head in the treatment unit and on the down gradient side of the impermeable barrier. The buildup of the hydraulic head in the discharge portion of the FGPRB trench may have been caused by inflow from deeper groundwater on the down gradient side of the trench (as evidenced by upward vertical gradients) and surface recharge.

A TPRB was installed subparallel to the groundwater flow direction at Pathway 2; between 200,000 and 400,000 gallons of contaminated groundwater were treated. Comparisons between up gradient and down gradient wells indicate a general reduction in the uranium concentration of about 90 percent, while the reduction in the concentrations of secondary COCs (nitrate [83%] and sulfate [82%]) was highly variable, with increases in some of the constituent concentrations noted in some samples. The strong upward vertical gradients in the bedrock monitoring wells in the vicinity of the trench indicate deeper groundwater discharge that could affect groundwater quality in the bedrock monitoring wells.

The low hydraulic gradient and recharge from the deeper groundwater flow system affected the operational success of the FGPRB and the TPRB demonstrations. Review of groundwater monitoring well data indicates a strong upward vertical component of flow; site characterization activities identified fractured bedrock and saprolite with remnant bedding along the lower boundary of the shallow groundwater flow regime. These factors contributed to a buildup of hydraulic head on the down gradient side of the trenches, which adversely impacted the hydraulic operation and treatment effectiveness of the systems. To counteract this hydraulic buildup, pumps had to be installed in the FGPRB treatment vault to move the contaminated groundwater through the treatment units and out the discharge manifold on the down gradient side of the impermeable barrier. For the TPRB, the trench had to be extended and an enhanced treatment zone had to be constructed several hundred feet away at a lower elevation to provide sufficient gradient to overcome this hydraulic buildup.

Health & Safety Issues

Health and safety issues were not encountered with either the Pathway 1 or Pathway 2 PRB demonstrations, other than those that would normally be encountered for any earth moving or similar construction project.

Regulatory Considerations

No exceptional regulatory requirements were imposed for construction and demonstration of the two PRB systems.

Commercial Availability

Installation of both PRB systems were accomplished with standard earth-moving and construction methods, utilizing readily available materials. No special training or techniques were required.

Future Plans

The FGPRB system at Pathway 1 will be modified by installation of a 1,200-foot long subsurface pipeline, which will extend from the treatment vault and connect to the east end of the TPRB. With installation of this pipeline, the new configuration will provide a sufficient groundwater gradient to operate the system in an entirely passive mode without any pumping.

Long-term monitoring of the removal actions will be conducted under the Y-12 Water Quality Program to evaluate the performance of the PRB technology in removing the COCs and to determine if additional actions are required.

Parties Involved with the Demonstration

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://www.em.doe.gov/ost under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The Tech ID for Passive Reactive Barrier is 46.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

The objective of the S-3 Ponds ORR Y-12 Plant demonstrations was to reduce the amount of contamination reaching Bear Creek through Pathway 1 and Pathway 2. Two different PRB systems that tried to utilize the hydrogeologic characteristics of each site, in conjunction with the hydraulic properties of the technology design, to capture and direct the contaminated groundwater through the treatment zone. The FGPRB system was installed at the Pathway 1 site, while the TPRB was installed at the Pathway 2 site.

The basic principles utilized in the design of the PRB technology are:

- The energy represented by the hydraulic gradient of the local groundwater flow regime, when combined with differences in the hydraulic properties of the PRB components, is sufficient to operate the treatment system in a purely passive mode.
- The reactive material utilized in the treatment unit is contaminant specific and will remove the target COC until its treatment properties are exhausted, at which time the material will have to be replaced by new media.

FGPRB Technology

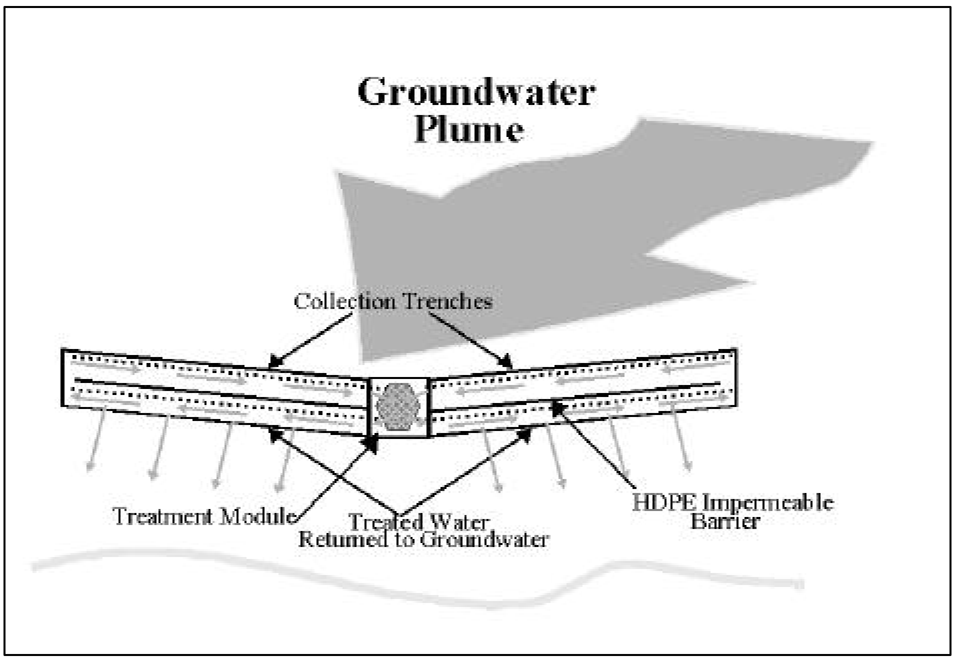

Figure 4. FGPRB schematic at ORR Pathway 1 Site.

The basic components of the Pathway 1 FGPRB are (see Figure 4):

- an impermeable barrier constructed in a sand-filled trench;
- a collection trench (that portion of the sand-filled trench on the up gradient side of the impermeable barrier) that was used to capture the contaminant plume;
- a discharge trench (that portion of the sand-filled trench on the down gradient side of the impermeable barrier) that was used to return the treated groundwater to the shallow groundwater flow system;

- a treatment vault (module) that contained pumping and sampling systems; and,
- a valve-control skid (not shown) that was located on the surface, which was used to control the individual treatment module components.

The impermeable barrier intercepts the groundwater flow and directs it through perforated polyvinyl chloride (PVC) pipes imbedded in the sand-filled trench to the treatment vault. Zero-valent iron was selected because of its ability to remove uranium by adsorption and reduction.

The sampling system was designed to monitor each phase of the treatment process without exposing personnel to hazardous conditions (i.e., the treatment vault is a confined space). After treatment, the groundwater is directed back to the valve-control skid, through the outlet valves, and discharged into the sand-filled trench on the down gradient side of the impermeable barrier.

The major components of the FGPRB constructed for this demonstration are described below:

1. **Collection Trench** – the collection trench (Figure 5), installed in December 1997 consists of two wing walls designed to funnel groundwater to a below-ground concrete vault. It was constructed essentially perpendicular to the direction of groundwater flow, approximately 220 feet long and 25 feet deep. A high-density polyethylene (HPDE) impermeable barrier was installed vertically in the middle of the trench. Groundwater quality analyses and tracer studies were conducted as part of the verification testing to ensure proper construction and liner integrity. Four-inch diameter perforated PVC drainpipes, for both collection and discharge, were placed in a sand backfill and installed on the up gradient and down gradient sides of the membrane, respectively. The collection drainpipe directs the contaminated groundwater to the treatment vault, while the discharge drainpipe distributes the treated groundwater on the down gradient side of the barrier.

Figure 5. FGPRB installation.

2. **Valve-Control Skid** – the valve-control skid consisted of electrically-driven isolation valves, controlled from the surface to direct the contaminated water through the treatment units, under

several different configurations. The collection and discharge drainpipes were connected to the valve-control skid with 1-inch diameter flexible hoses with quick-release fittings.

3. **Pumping System** – the shallow hydraulic gradient and relatively low groundwater flow rate at Pathway 1 required installation of a pumping system that could be used to supplement flow through the FGPRB treatment units.

4. **Sampling System** – the sampling system consisted of monitoring wells and sample collection ports throughout the FGPRB system. Pairs of monitoring wells (8 pairs in the east wing and 4 pairs in the west wing) were located in the trench, on the up gradient and down gradient sides of the HPDE barrier to collect data on hydraulic head and water quality. Sample collection ports were also included at various locations throughout the treatment system to monitor the effectiveness of the entire system or individual components.

5. **Treatment Vault** – the contaminated groundwater captured on the up gradient side of the impermeable barrier is directed to the treatment vault and through the treatment units. The water could be directed through one or both of two different treatment systems for removal of some, or all, of the target COCs. Treatment media were contained in 55-gallon drums to facilitate testing and replacement. After passing through the units, the treated groundwater is directed to the discharge drainpipe for discharge on the down gradient side of the HDPE barrier. While the treatment system was designed to operate passively, site conditions were such as to limit the quantity of groundwater that could flow through the system. Consequently, pumps were installed to ensure that the required flow rates to effectively test the two treatment trains were obtained.

6. **Treatment Systems** – Two different treatment systems that could remove some or all of the COCs were demonstrated:

   - **Treatment Train** – the treatment train included three 55-gallon canisters that were run in series (see Figure 6) and provided: (1) initial pH adjustment using a mixture of magnesium hydroxide, iron and gravel; (2) removal of uranium and other radionuclides using iron filings (zero-valent iron); and, (3) nitrate removal using a mixture of iron and peat. Due to the low pH and high bicarbonate concentration (buffering capacity) of the contaminated groundwater, initial pH adjustment in Canister 1 was required to prevent oxidation of the iron and subsequent discharge of high ferrous iron concentrations in the effluent. The treatment train was constructed so that samples could be collected from the inlet and outlet of the entire train or individual treatment canisters.

Figure 6. FGPRB electrochemical treatment cell.

   - **Electrochemical Cell** – the second treatment system was a single 55-gallon drum filled with zero-valent iron that had electrodes at the top and bottom of the unit. As contaminated groundwater passes through the zero-valent iron, a small current is applied to the system to provide electrochemical treatment. The applied current increases the pH of the groundwater, which reduces the rate of iron oxidation (and lowers the ferrous iron concentration in the effluent) and increases the reductive capacity of the iron, thereby increasing the effectiveness of contaminant treatment and removal (especially for uranium and other radionuclides).

TPRB Technology

The TPRB initially constructed at Pathway 2 (see Figure 7) consisted of a trench 225 ft long and 30 ft deep that was installed subparallel to the shallow groundwater flow direction, in accordance with the design illustrated in Figure 8. The contaminated groundwater is captured on the up gradient end of the trench, funneled through the reactive iron media in the middle of the trench for contaminant removal, and discharged from the down gradient end of the trench.

Figure 7. TPRB construction.

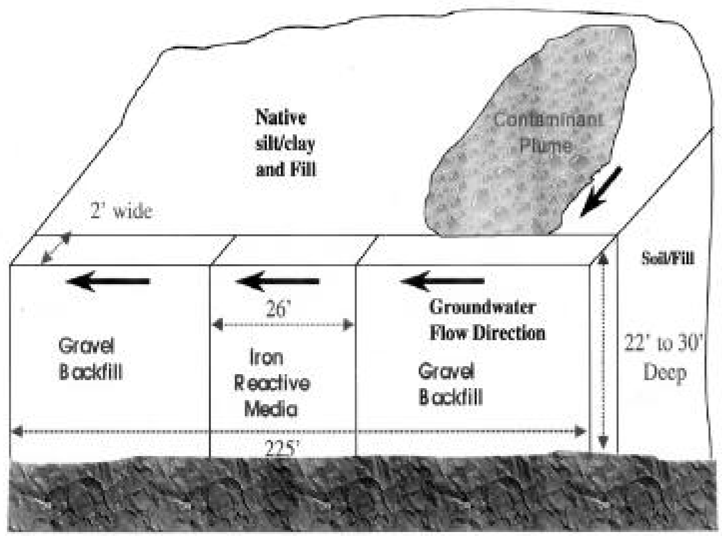

Figure 8. TPRB schematic at ORR Pathway 2 (MSE 1999a.

System Operation

FGPRB Technology

Contaminated groundwater is collected on the up gradient side of the impermeable barrier and directed into the treatment vault through the 4-inch I.D. perforated collection drainpipes. The drainpipes enter the concrete treatment vault through a penetration boot that is about four feet above the floor. At this point, the drainpipe is reduced to the 1-inch diameter flexible hose that is connected to the valve-control skid. From the valve-control skid, the water is directed to a collection tank that provides a reservoir of water prior to entry into the treatment system. Check valves prevent backflow from occurring in the system.

The collection tank is equipped with a vent that remains open until the tank is full and then closes to achieve pressure equilibrium with the groundwater. A pressure-relief valve is also incorporated to prevent over pressurization of the system. From the collection tank, water is pumped to a head tank and then flows to the treatment system(s). The system can be configured for the water to flow passively (using gravity) from the head tank to either one or both of the treatment systems, or it can be directed through the treatment units under pressure by using an auxiliary pump and head tank. Water-level switches in the head tank determine the passive or active operating mode. When the pressure head in the collection tank falls below the lower water level in the head tank, the auxiliary pump is activated to achieve flow. When the pressure head in the collection tank exceeds the upper water level in the head tank, the auxiliary pump is stopped and passive flow resumes.

The treatment vault contains the treatment units as well as the electrical components of the system. To prevent damage to the electrical components, a sump and associated pump is used to maintain the water level so that the electrical components do not become submerged. Three water-level switches control operation of the sump pumps in the vault. If the water level in the sump cannot be controlled, an alarm sounds to indicate that the vault is starting to flood and action must be taken to prevent the electrical components from becoming submerged.

There are several pressure-regulating valves that control the pressure in the system when the auxiliary pump is being used. If over pressurization occurs, excess water is diverted to the sump to prevent damage to the treatment units. In addition, an electrically actuated valve controls the output from the collection tank, which is generally open except when the sump is being pumped out.

Treated water is directed through the valve-control skid to the outlet pipes that were placed in an engineered porous media for discharge on the down gradient side of the HDPE impermeable barrier. Check valves prevent backflow of the treated water through the treatment units, while two electrically driven isolation valves can be used to isolate the exit pipes.

The entire FGPRB system can be operated and controlled from a control panel, located at the surface (see Figure 9).

Figure 9. FGPRB surface control panel.

Operation of the system requires a 110-volt electrical supply for the two small pumps and the electrically controlled valves. Operators must be certified at the Radiation Worker II level because of the radioactive contaminants in the waste stream. Water monitoring must be conducted one day per month to verify treatment effectiveness and to ensure that breakthrough of the treatment units has not occurred.

The life expectancy of the reactive media is not known, but is estimated to be months or years, depending upon the influent concentration of the COCs. Media replacement will be required when the monthly monitoring program detects breakthrough of the COCs, if the media become plugged from solids accumulation, or if the flow rate through the system is substantially reduced or stopped. The zero valent iron treatment media (for removal of radionuclides) will be considered a low-level radioactive waste for disposal purposes.

TPRB Technology

The TPRB system installed at the Pathway 2 site is completely passive and requires no electricity for operation. To increase the groundwater capture zone and enhance the treatment operation, the original TPRB system was modified by extending the trench an additional 125 feet (for a total length of 350 feet) to the west and installing a second treatment zone. The extraction well illustrated in Figure 10 serves as a passive connection point for a siphon line and does not include any pumping apparatus. The nonreactive portion of the trench was filled with gravel; approximately 48 piezometers were installed at the site to monitor water levels, including six multiport wells installed in the treatment media.

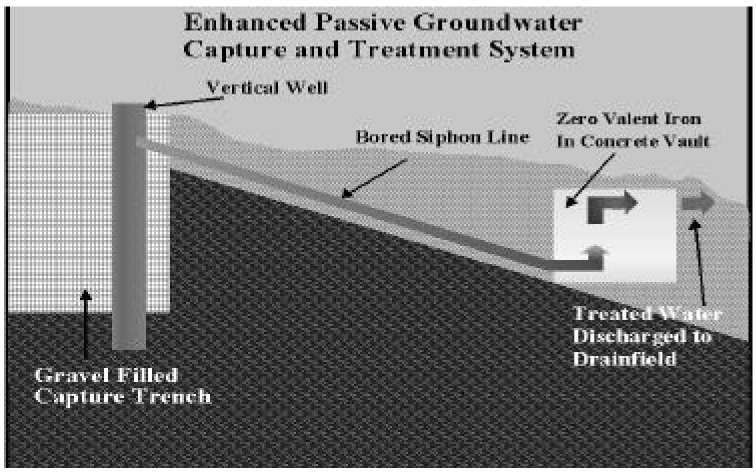

Figure 10. TPRB modifications at ORR Pathway 2 (MSE 1999a).

A continuous trenching machine was used to construct the 125-foot extension to avoid impacts to the formation and reactive media permeability as well as the groundwater geochemistry. With this construction method, simultaneous excavation of the soil and residuum, and backfilling of the trench with the porous and reactive media was achieved. The west end of the trench extension is connected via a siphon system to a down gradient treatment unit located 750 feet to the west. The siphon system consists of a 12-inch diameter well and 2-inch diameter riser pipe that is connected to two concrete boxes containing 13 tons of reactive iron media (each) (see Figure 11). The discharge from this treatment unit is directed to a rock-filled subsurface drainfield for disposal.

Because of the passive-system mode of operation, the operating and maintenance requirements are relative minor, although operators must be certified at the Radiation Worker II level due to the radioactive contaminants in the waste stream. Water monitoring must be conducted one day per month to verify treatment effectiveness and to ensure that breakthrough of the treatment units has not occurred.

The life expectancy of the reactive media is not known, but should be similar to that in Pathway 1.

Figure 11. Enhanced TPRB treatment units.

SECTION 3
PERFORMANCE

Demonstration Plan

The ORR is adjacent to the City of Oak Ridge, Tennessee. The Bear Creek Valley trends east to west and is approximately 10 miles long. The west end of the valley is bounded by the Clinch River at the Grassy Creek Embayment on Watts Bar Lake, while the location of a groundwater divide at the west end of the Y-12 Plant marks the east end of the Bear Creek watershed. The ORR is underlain by the Nolichucky formation, which consists primarily of shale interbedded with intraclastic limestone, thick fossiliferous limestone, and oolitic limestone. Overall, the permeability of the formation is relatively low (MSE, 1998c).

Pathway 1 and Pathway 2 consist of a shallow groundwater flow system that empties into the upper portion of Bear Creek (see Figure 2). The contaminant plume originated from the former location of four unlined ponds that received liquid waste discharges from the Y-12 Plant and other sources until 1983. Contaminants included radionuclides (uranium and technetium), nitrates, sulfates, metals, and organics. During the last year of operation, the ponds reportedly received 2.7 million gallons of liquid wastes that essentially percolated into the shallow groundwater. The ponds were filled and capped in 1988, and the site is currently occupied by a parking lot.

The Pathway 1 and Pathway 2 contaminant plumes are associated with the historical discharges from the ponds, while water percolating through the sludge left in the bottom of the ponds contributes a lesser amount. Uranium concentrations in Pathway 1 were as high as 2.6 mg/L, while those in Pathway 2 were up to 1.7 mg/L. The U.S. Environmental Protection Agency (USEPA) has set goals for the reduction of total uranium flux into the Bear Creek watershed, although the contributions from Pathway 1 and Pathway 2 are relatively small (Jacobs 1998). The goal of the demonstrations was to reduce the uranium concentrations to the Bear Creek watershed without generating any undesirable byproducts. Because the majority of the uranium flux into the Bear Creek watershed comes from other sources, the reduction or elimination of uranium from Pathway 1 and Pathway 2, and not Bear Creek, was the criterion for success for the demonstrations.

The major components of the FGPRB and TPRB technologies that were evaluated during the demonstration were:

- could the local hydraulic gradient provide the necessary energy for passive operation of the groundwater collection and treatment systems; and
- could the reactive media (zero valent iron) reduce the concentrations of uranium and other constituents in the process stream to acceptable levels?

Results

Approximately 133,000 gallons of contaminated groundwater from Pathway 1 were collected and treated during the FGPRB demonstration. In general, the groundwater collection system operated satisfactorily, although an increase in the hydraulic head on the down gradient side of the treatment unit, which created some problems with operation of the system, was observed. While the treatment system was effective in reducing uranium concentrations to acceptable levels, the success in reducing the concentrations of other contaminants in Pathway 1 was variable (ORNL 1999). Table 1 summarizes influent and effluent uranium concentrations and removal efficiencies for the FGPRB treatment system.

Table 1. Summary of FGPRB uranium data

Date	Inlet Concentration (mg/L)	Outlet Concentration (mg/L)	Percent Reduction
9/16/98	0.24	0.001	99.6
9/17/98	0.249	0.003	98.8
9/21/98	0.089	0.0054	93.9
9/23/98	0.094	0.0064	93.2
9/29/98	0.0318	0.0063	80.2
12/0198	0.151	0.0051	96.6

For the TPRB treatment system, effective removal of uranium and varying success for the COCs were noted as well. Because the original TPRB system did not have single entry and exit points, the removal efficiency for the system had to be estimated from the uranium concentration up gradient and down gradient of the trench. While it is not possible to quantify exact treatment efficiency, Table 2 provides a summary of uranium concentrations from up gradient and down gradient wells. Review of these data indicates an overall treatment efficiency in the range of 75 to 90 percent, as exhibited by uranium concentrations in the up gradient wells in the 0.2 – 0.5 mg/L range and in the down gradient wells of usually below 0.05 mg/L. Also, uranium concentrations in the down gradient wells exhibited a downward trend over time, which was probably due to dilution of pre-existing contamination (ORNL 1999). With modifications to the initial TPRB system, the single entry and exit points will facilitate improved monitoring of the treatment effectiveness.

Table 2. Summary of TPRB uranium data

Date	Up gradient Wells		Down gradient Wells			
	DP-13	TMW-11	TMW-7	TMW-9	DP-20M	DP-23M
12/10/97	N/A	0.535	0.102	0.110	N/A	N/A
12/15/97	N/A	0.224	0.163	0.089	N/A	N/A
12/19/97	N/A	0.318	N/A	0.094	N/A	N/A
02/12/98	N/A	0.176	0.003	<0.001	N/A	N/A
03/04/98	0.842	0.169	0.005	0.001	N/A	N/A
04/07/98	N/A	N/A	N/A	N/A	0.002	N/A
04/20/08	0.542	0.220	0.004	0.016	0.010	0.002
05/11/98	0.734	0.207	0.007	0.009	0.002	0.008
06/01/98	0.503	0.154	0.017	0.005	BD	BD
09/01/98	N/A	0.143	N/A	<0.001	N/A	N/A
11/98	0.508	N/A	0.016	BD	0.007	<0.001
01/26/99	0.556	0.345	0.003	0.040	0.019	<0.001

Note: All concentrations expressed as mg/L, rounded to the nearest 0.001.
N/A = Note Analyzed.
BD = below detection limit.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

The PRB technologies were designed to passively capture and treat contaminated groundwater. Because the PRB collects and treats the contaminant plume, the most relevant competing technology is the pump and treat system, which is considered to be the baseline technology.

Improvements in barrier construction methods and contaminant removal technologies greatly enhance the cost effectiveness of PRB technology. As a result, the PRB technology is well-suited to address shallow groundwater contamination at many different types of DOE, DoD, and private sector sites, including weapons systems and munitions manufacturing facilities, chemical production plants, oil refineries, semiconductor manufacturing plants, and existing or former mines or acid mine drainage sites.

Advantages and disadvantages of these two technologies are summarized below:

Passive Reactive Barrier

- Advantages
  - Passive operation has low manpower and energy requirements.
  - Contaminant concentrations are rapidly reduced.
  - Works at sites with low-permeability materials.
- Disadvantages
  - The intercept trench/impermeable barrier for the PRB technology must be constructed to direct all, or a substantial portion, of the contaminated groundwater to the treatment cell.
  - The effectiveness of the PRB technology is decreased at sites without a relatively impermeable lower boundary, such as areas underlain by fractured media.
  - The reactive media may have to be replaced periodically to maintain treatment effectiveness.
  - Depth of installation is currently limited to less than fifty feet.

Pump and Treat System

- Advantages
  - Under ideal hydrogeologic conditions, substantial cleanup may be achieved with a minimum number of wells.
  - Construction of a barrier may not be required.
- Disadvantages
  - Due to the potential need for continual pumping, it may have high labor and energy requirements.
  - It may not work well, or will be more difficult, in settings with low-permeability materials.
  - An above-ground treatment system (plant) is required.
  - It may require additional environmental permits or more advanced treatment to meet applicable water-quality goals or pretreatment standards prior to discharge.

Technology Applicability

To evaluate the potential for using PRB technology at other locations, the following factors must be considered.

Contaminant Distribution

The contaminant distribution should be well defined, relatively shallow, and with limited aerial extent. For best results, the groundwater collection trench should be located directly down gradient of the contaminated area and needs to be long enough to capture the width of the contaminant plume.

Hydrogeology

The shallow geology should be relatively homogeneous and must be underlain by a low-permeability layer (aquitard). For passive operation, the technology relies on the ability to intercept contaminated groundwater, leverages the energy of the local hydraulic gradient and gravity, and capitalizes on differences in the hydraulic properties of the aquifer matrix and PRB materials of construction. Because of these reasons, the shallow ground flow regime must be relatively isolated from deeper systems that may increase contaminant or hydraulic loading to the system. The degree of hydraulic connection between shallower and deeper groundwater flow systems can affect efficacy of PRB technology.

Reactive Material Selection

The type of reactive material will be dependent upon the COCs to be removed from the contaminant plume. Contaminant-specific reactive materials and treatment trains can be used to remove one or multiple COCs. Bench-scale testing is recommended for selection and design of the reactive media.

Scale-up Requirements

The use of PRB technology to address contaminant plumes larger than the one for the ORR demonstration is technically feasible and straightforward. For the FGPRB, the collection trench must be oriented in such a manner as to direct (funnel) the captured groundwater to the treatment module (gate). For the TPRB, the collection trench must direct the captured groundwater to and through the reactive treatment zone in the trench. However, as the length of the trench increases, the potential for subsurface discontinuities, which could adversely impact the PRB performance, also increases. With this increase in capture zone area, there is also an increase in the volume of groundwater and total contaminant loading that will be directed to the treatment unit(s). These factors will affect the size of the treatment unit(s), the load-up rate and life expectancy of the reactive media, and how often the reactive media will have to be replaced. It may be more cost effective to install several smaller PRB systems side-by-side, rather than relying on one very large PRB system.

Patents/Commercialization/Sponsor

The University of Waterloo, Ontario, Canada, holds a number of patents related to the PRB technologies described herein. The University's licensed agent is EnviroMetal Technologies, Inc. (ETI), also based in Waterloo, Ontario, Canada. ETI currently holds the license for the funnel-and-gate technology, Waterloo sealable joint sheetpile, and the use of zero-valent iron for removal of organic and inorganic compounds. ETI requires a license fee of 15% of a project's direct construction cost when these technologies are utilized (MSE 1999b).

The PRB technology is commercially available and can be installed without specialized services. Similar technology applications (slurry walls and impermeable barriers with groundwater extraction and treatment) have been used by private industry for years to isolate and treat contaminants.

The demonstration project described herein was sponsored by the DOE, Office of Science and Technology (EM-50) and the Environmental Restoration Program (EM-40); it included the following participants: MSE, ORR, Bechtel Jacobs Company, L.L.C. (Jacobs), USEPA National Risk Management Research Laboratory, and ETI.

SECTION 5
COST

Methodology

The primary source of cost information presented herein was developed by MSE (1998a). While the installation, startup, and initial operation costs were documented for the PRB demonstration projects at ORR, additional time must pass before the long-term operation and maintenance (O & M) costs can be documented with any accuracy. Specifically, the actual contaminant loading rate and capacity for the reactive media, and therefore the life expectancy of the treatment units, can only be documented through operation of the system. The frequency at which the reactive media units must be replaced, and the cost of this replacement activity will be determined through ongoing system operation. Also, operational problems caused by a build up of the hydraulic head on the down gradient side of the impermeable barrier for the FGPRB system affected overall system efficiency and increased system costs.

Cost Analysis

While the long-term O & M costs will be developed through operation of the FGPRB system at ORR, the actual system installation costs are summarized in Table 3 (MSE 1998c). Costs for the TPRB system have not been fully developed yet and thus, are not included in this analysis.

To facilitate evaluation for similar applications, total costs were converted to a cost per square foot of FGPRB technology that was installed in the collection trench. For purposes of the cost analysis, the following assumptions were used:

- the total length of the collection trench (funnel) and gate (treatment vault) was approximately 220 feet, with 11.5 feet (5.23%) comprised of the treatment vault and 208.5 feet (94.77%) comprised of the HPDE impermeable barrier and collection trench;
- the impermeable barrier/collection trench was considered to be a two-dimensional planar feature approximately 23.5 feet deep by 208.5 feet in length, with a total area of 4,899.75 square feet;
- the treatment vault was considered to be a two-dimensional planar feature approximately 11.5 ft wide by 23.5 ft deep, with a total surface area of approximately 270.25 square feet; and,
- the total surface area of the FGPRB, when viewed as a two-dimensional planar feature, was 5,170 square feet.

Based on these assumptions, 94.58% of the FGPRB surface area was comprised of the impermeable barrier and 5.42% was comprised of the treatment vault. Consequently, the cost for the impermeable barrier/collection trench construction was $359,404 and the cost was for the treatment vault construction was $20,596. Based on these figures, the average per square foot installation cost was $73.26. However, because of the treatment vault construction characteristics (i.e., a hollow solid), the average per square foot installation cost must be adjusted so that the average overall per square foot installation cost is $75.45. Cost estimates for the baseline pump and treat technology were not prepared for either of the PRB technology demonstration sites.

Table 3. FGPRB installation cost summary

Activity	Cost	Cost/square foot
Installation of barrier wings and vault and preparation for installation of treatment units	$380,000	$75.45
Initial pumping of guar slurry (for barrier construction)	$75,000	$14.49
Sealing of treatment vault and remediation of guar slurry	$75,000	$14.49
Project management and labor during construction	$168,000	$32.56
Barrier testing	$44,800	$8.66
Treatment skid and control panel installation	$200,000	$38.65
TOTAL	$943,300	$183.00

Cost Conclusions

Construction modifications will convert the FGPRB system to a completely passive mode of operation, while additions to the TPRB system will help to develop better assessment treatment efficiencies. These modifications should help reduce O & M costs, but no quantitative costs savings have been determined at this time.

SECTION 6
OCCUPATIONAL SAFETY AND HEALTH

Summary

The baseline technology (groundwater pump and treat) presents an exposure risk to site workers from investigation-derived waste, groundwater monitoring well purge water, well drilling equipment, and groundwater monitoring equipment. PRB technology has a slightly higher exposure risk due to the methods of construction. However, after installation is complete, exposure to site workers should be less because they are not as close to the contaminants or equipment as with the baseline technology.

Technology-Specific Health and Safety Risks

Additional potential hazards from PRB installation include:

- exposure to large quantities of contaminated soil and groundwater during trench construction activities; and
- work in or around confined space when installing reactive media units in the treatment vault or when assisting with impermeable barrier installation in the trench.

These hazards must be mitigated as required by OSHA and other regulations. Engineering controls for these hazards generally include restricting worker proximity and equipment operation in areas where these hazards may be present.

Worker Safety

PRB technology generally does not require the implementation of extraordinary health and safety measures other than what is typically implemented at sites utilizing conventional remediation technologies. Standard measures include:

- Level D personal protective equipment (PPE), or Level C for workers handling potentially radiological contaminated equipment;
- applicable OSHA training; and
- monitoring for site-specific potential airborne contaminants or emissions that may be present during operations.

General hazards include:

- slip, trip, and fall;
- crush hazards from heavy equipment; and
- electrocution hazards from overhead power lines.

Lessons Learned

All aspects of the construction and installation of the FGPRB and TPRB technologies were conducted safely.

SECTION 7
REGULATORY AND POLICY ISSUES

Regulatory Considerations

There were minor regulatory issues associated with the demonstration projects, as described in the following sections.

Installation Permits

Demonstration of the PRB technologies satisfied the criteria for a Categorical Exclusion, which is defined as an action that does not involve significant environmental impacts (air, noise, and water quality). Once these criteria are met, the Categorical Exclusion document is formally approved by the Demonstration Site Environmental Coordinator. In addition, site specific permits for ground penetration and confined space entry were obtained from the ORR Contractor Technical Representative, as necessary.

Because a Categorical Exclusion was obtained for the Pathway 1 and Pathway 2 demonstration projects, the nature and cost of required environmental permits were probably less than those for any competing technologies that may have been implemented. For example, a typical pump and treat system that discharges to a surface water body will require a National Pollutant Discharge Elimination System (NPDES) permit. If the surface treatment plant discharges to a publicly owned treatment works, some sort of pretreatment is usually required. Even when the discharge from the pump and treat system is injected into the aquifer for plume control, additional water quality standards may have to be met to minimize potential aquifer impacts.

CERCLA Evaluation Criteria

The Pathway 1 demonstration was considered to be a non-time critical action under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The PRB demonstrations were incorporated into the CERCLA cleanup process being conducted at the S-3 Ponds Site (Jacobs 1998).

Based on the results of this demonstration, the CERCLA Evaluation Criteria were addressed as follows:

1. *Protection of human health and the environment* – the PRB technology had a positive effect on human health and environment because it reduced contaminant concentrations in the groundwater to acceptable levels.

2. *Compliance with Applicable or Relevant and Appropriate Requirements (ARARs)* – the PRB technology satisfied regulatory requirements, both from the standpoint of installation activities and reductions in contaminant concentrations.

3. *Long-term effectiveness and performance* – the PRB technology satisfied the initial performance criteria. The residual risk associated with the waste stream has not been evaluated, and the nature and magnitude of the waste streams generated over the long term is not yet known.

4. *Reduction of toxicity, mobility, or volume through treatment* – the PRB technology reduced the toxicity of the contaminated groundwater by lowering contaminant concentrations and reduced the mobility of the contaminants by channeling (diverting) the contaminated groundwater towards the treatment media.

5. *Short-term effectiveness* – the effectiveness of the PRB technology was demonstrated with respect to the acceptability of impacts during construction and contaminant remediation over the short term. Performance over the long term will require continuing evaluation.

6. *Implementability* – technical implementation is straightforward because installation is very similar to that for conventional impermeable barriers.

7. *Costs* – capital and O & M costs appear favorable when compared with more established methodologies.

8. *State (support agency) Acceptance* – regulatory issues were not identified with the PRB technology demonstrations.

9. *Community acceptance* – community acceptance issues were not identified with the PRB demonstrations.

Risks, Benefits, Environmental and Community Issues

The following requirements were implemented for the PRB technology demonstrations and are generally applicable to more conventional treatment methods as well:

- A Field Implementation Plan must be developed to identify project goals and requirements and to ensure successful project execution.
- A Health and Safety Plan must be prepared and acknowledged by all parties involved in the project and kept on site at all times during construction and operation of the system.
- Pre-construction environmental, health, and safety (EH&S) training is required for all project site workers and management personnel. Each construction day must begin with a safety meeting, and records must be kept in a logbook. Specialized training may be required for sites with certain types of contamination (radioactive wastes).

Socioeconomic impacts will not normally be a concern due to the small scale and low manpower requirements for PRB technology installations. Potential worker exposures should not be a concern, provided that appropriate EH&S training is provided prior to, and during, construction.

SECTION 8
LESSONS LEARNED

Implementation Considerations

The following lessons learned and recommendations/observations are based on installation and demonstration of the PRB technologies at Pathway 1 and Pathway 2 (MSE 1999a, MSE 1999b).

- **Soil stability** – this was a serious concern during construction of the intercept trenches and treatment vault because of construction problems associated with slope failures (the use of a continuous trencher at Pathway 2 helped alleviate this problem).
  - a thorough geotechnical site investigation is required to delineate appropriate construction methods and techniques;
  - geophysical techniques may be useful to locate debris or other site anomalies that could affect PRB system construction and operation;
  - trench excavation should occur in short sections and be backfilled as soon as possible;
  - early placement of base materials will help stabilize the initial excavation;
  - the placement of stockpiled materials and the movement of heavy equipment near the trench should be minimized to prevent or minimize problems with trench stability.

- **Valves and Piping** – numerous operational and maintenance problems can be directly linked to leaking and malfunctioning valves and piping, which can be prevented by implementing the following recommendations.
  - valves and connections should be selected to minimize the number of leak points, account for pipe expansion, and accommodate isolation of system components for troubleshooting and maintenance;
  - backfill operations must be performed in accordance with construction and design specifications to avoid damage to system components and to maintain proper grade;
  - easy access to valves must be incorporated into the PRB technology design to facilitate operation and maintenance of the system.

- **Damage to HDPE Vessels** – the integrity of the HPDE liner is crucial to the proper functioning of the PRB technology.
  - HDPE welds must be carefully inspected upon their arrival at the job site;
  - ladders and other ancillary equipment should be attached mechanically by the manufacturer.

- **Utilities** – utility locations may not agree with current or historical site drawings or the recollections of site personnel.
  - anticipate that above ground and subsurface utilities may be present in the project area, even when current maps do not indicate that any utilities are present; this is especially true for older facilities;
  - use electronic equipment to locate utility lines, if practical.

- **Equipment and Resources**
  - Do not assume that plant-supplied equipment or supplies will be available when needed;
  - Coordinate and plan equipment needs and resource issues well in advance of project needs.

- **Project Record and Documentation Requirements**
  - project records should be developed concurrently during project execution because this information is much more difficult to obtain after the work has been completed;
  - project records should be submitted weekly to the Contractor's Technical Representative to properly document project activities.

- **Verification Testing**

  — tracers are effective, in a qualitative sense, in identifying possible problems with barrier integrity;
  — tracers are only marginally effective for quantifying the degree or extent of barrier leaks.

- **HDPE Membrane Installation**

  — installation of the HDPE membrane and intercept trench can be expedited with the use of a guar slurry, which provided excellent trench wall support and prevented slope failures during construction;
  — guar slurry can be awkward to work with during trench construction and modifies the groundwater chemistry for an unknown period of time.

Technology Limitations and Needs for Future Development

The following limitations need to be addressed before PRB technology can be more widely implemented.

- **Depth of contamination** – many contamination problems exist at significant depth, while current barrier installation technology is only effective at relatively shallow depths (less than 50 feet). Enhanced construction methods need to be developed to increase the practical depth of barrier construction.
- **Barrier/intercept trench stability** – achieving structural stability for the installed barrier is a challenge; slurries are often used during construction to enhance barrier stability. However, these slurries can impact local groundwater chemistry and aquifer permeability; methods of achieving stability without using slurries should be developed.
- **Reactive media life expectancy** – because PRB technology is relatively new, little is known about the length of time for which the reactive media will perform as designed. Tests are needed to evaluate media life expectancy.

Technology Selection Considerations

Prior to selecting PRB technology for a specific site application, the following issues must be considered in the decision-making process.

- **Nature of contamination** – is there a reactive media that will remove the COCs with acceptable efficiency and to the required concentration? Bench-scale treatability studies should be conducted to select and design the most appropriate media and PRB technology to meet site-specific conditions.
- **Depth of contamination** – is the depth of contamination within the limits at which a PRB system can be successfully installed?
- **Hydrogeological characteristics** – is an aquitard (or low permeable layer) present to provide a relatively impermeable floor beneath the PRB system? What are the horizontal and vertical groundwater flow directions and gradients and will they adversely impact the passive PRB technology design?
- **Cleanup goals and timeframe** – the PRB technology can be very effective in removing specific contaminants. However, a passive mode of operation, coupled with a low-permeability setting, results in slow, but effective, contaminant removal. Is sufficient time available to achieve cleanup goals and meet regulatory requirements using this method?

APPENDIX A
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APPENDIX B
ACRONYMS AND ABBREVIATIONS

AMD	Acid Mine Drainage
ARARs	Applicable or Relevant and Appropriate Requirements
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
COC	Constituent (contaminant) of Concern
DOE	U.S. Department of Energy
DoD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
EH&S	Environmental Health and Safety
ETI	EnviroMetal Technologies, Inc.
FGPRB	Funnel and Gate Passive Reactive Barrier
HDPE	high-density polyethylene
mg/L	milligrams per liter
MSE	MSE Technology Applications, Inc.
NPDES	National Pollutant Discharge Elimination System
ORNL	Oak Ridge National Laboratory
ORR	Oak Ridge Reservation
OSHA	Occupational Safety and Health Administration
OST	Office of Science and Technology
PPE	Personal protective equipment
PRB	Passive Reactive Barrier
PVC	polyvinyl chloride
SITE	Superfund Innovative Technology Evaluation (EPA Program)
TPRB	Trench Passive Reactive Barrier
µg/L	micrograms per liter
VOC	volatile organic compounds